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USAGE

An International Quiet Ocean Experiment

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ABSTRACT. The effect of noise on marine life is one of the big unknowns of current marine science. Considerable evidence exists that the human contribution to ocean noise has increased during the past few decades: human noise has become the dominant component of marine noise in some regions, and noise is directly correlated with the increasing industrialization of the ocean. Sound is an important factor in the lives of many marine organisms, and theory and increasing observations suggest that human noise could be approaching levels at which negative effects on marine life may be occurring. Certain species already show symptoms of the effects of sound. Although some of these effects are acute and rare, chronic sublethal effects may be more prevalent, but are difficult to measure. We need to identify the thresholds of such effects for different species and be in a position to predict how increasing anthropogenic sound will add to the effects. To achieve such predictive capabilities, the Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO) are developing an International Quiet Ocean Experiment (IQOE), with the objective of coordinating the international research community to both quantify the ocean soundscape and examine the functional relationship between sound and the viability of key marine organisms. SCOR and POGO will convene an open science meeting to gather community input on the important research, observations, and modeling activities that should be included in IQOE.

INTRODUCTION

Does the noise made by humans harm marine life? At present, we can offer only preliminary answers to this important question, for only a few species. We know that the ocean has become more industrialized and that the noise levels associated with human activities have increased (NRC, 2003). For example, in areas where measurements have been made, anthropogenic noise in the ocean has been increasing across much of the frequency spectrum (Andrew et al., 2002; McDonald et al., 2008), and especially at lower frequencies (< 500 Hz; Frisk, 2007). Increases in noise from human activities add to the many natural sources of sound in the ocean, such as waves breaking, rain, and ice movement, and the sounds of the marine animals themselves (Figure 1). Given the spatial and temporal complexity and variability in all sound sources, the relative contribution of anthropogenic noise is not always readily distinguishable.

The combined effects of temperature and pressure in the deep ocean create a sound channel by which acoustic waves can be transmitted over large distances, sometimes hundreds of kilometers, and often much further. The complex pathways taken by this sound affect the final received levels, but if they are averaged through time at the receiver, they provide an integrated signal defined by the relative locations of all the sound

[1]The authors of this article were the attendees at a meeting, held at the University of Rhode Island from October 27–29, 2010, to discuss the feasibility of conducting an experiment to examine the effects of sound on life in the ocean.

producers, the architecture of the ocean basin, and the properties of the water through which the sound has passed. It is sometimes possible to distinguish among different sound sources based on sound characteristics.

Humans introduce noise to the ocean through many different activities. Each source may have different effects, depending upon the frequency range, its intensity, and whether it is an intermittent, pulsed, or continuous sound. Some anthropogenic sounds—such as some military sonars, seismic air guns used extensively for oil and gas exploration, and pile driving—are both impulsive and high intensity. Such sounds can elicit strong negative reactions, or even physical injury, in some species, a concern that has led to higher levels of scrutiny for many of those sources. Recently, military sonars have been a particular focus of attention because of their association with the stranding of beaked whales (Cox et al., 2006). Nevertheless, the acute effects of sonars upon beaked whales probably occur only rarely because the effects of sonars themselves co-vary with other factors, such as context of the exposure (i.e., bathymetry, presence of surface temperature ducts, behavior, and number of naval vessels). Animal strandings are probably the most easily observed end point of a syndrome of behavioral responses to sound (Boyd et al., 2007), leading through some unknown progression to physical harm and/or mortality. There is a strong suspicion, supported by increasing evidence, that a similar syndrome of reduced capacity to perform normal life functions is present across a wide range of marine fauna, including fish (Slabbekoorn et al., 2010) and marine mammals (Southall et al., 2007; Tyack, 2008).

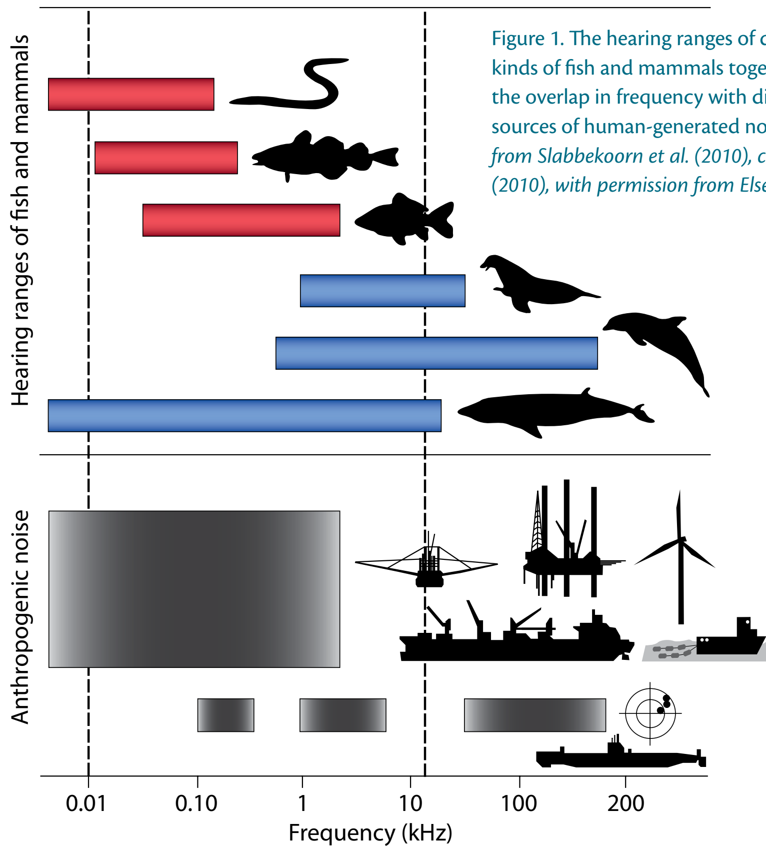

Figure 1. The hearing ranges of different kinds of fish and mammals together with the overlap in frequency with different sources of human-generated noise. *Modified from Slabbekoorn et al. (2010), copyright (2010), with permission from Elsevier*

A major unanswered question is whether anthropogenic noise has a significant impact on the fitness of individuals within populations that jeopardizes the viability of those populations. The US National Research Council addressed this question in its 2005 report on marine mammal populations and ocean noise (NRC, 2005), but the principles apply equally to all forms of marine life. We reflect this issue diagrammatically in Figure 2. The NRC report developed an approach known as Population Consequences of Acoustic Disturbance (PCAD), which defined a rationale for developing assessments of the significance of sublethal effects and for identifying the most important gaps in our knowledge. Our problem now is to define the functional relationships between behavioral or physiological responses to sound and population effects that are required for this assessment process to work.

Shipping is an important anthropogenic sound source (Wenz, 1962). The volume of cargo transported by sea has been doubling approximately every 20 years (http://www.marisec.org/shippingfacts/worldtrade/volume-world-trade-sea.php), resulting in an increase in anthropogenic sound. Although the systematic measurement of sound in relation to these changes is incomplete, the current estimate is that expanded shipping, which is directly correlated with increased global economic activity, has been accompanied by an increase in anthropogenic sound for frequencies below 500 Hz (Frisk, 2007). Over the past few decades, the shipping contribution to ambient noise has increased by as much as 12 dB above the natural background level in some locations (Andrew et al., 2002; Hildebrand, 2009). We also know that offshore oil and gas exploration and production, as well as development of renewable energy, have expanded during the same period, as has the fishing industry.

DEFINING THE QUESTIONS

Many animals use sound in the ocean, either passively to listen and orient relative to their surroundings, or actively as they produce sound to communicate or to search for prey or for objects; in some cases, their use of sound is a byproduct of other activity. Active use of sound is relatively easy to detect, but passive use is not. It is likely that most multicellular marine organisms use sound passively as a way of sensing the environment, including listening for prey and predators, and changing behavior in relation to weather and obstacles (including moving ships or static propellers such as are proposed for tidal turbines). The idea that animals may use something analogous to "acoustic daylight" (Buckingham et al., 1992) to gain an image of their surroundings is gaining momentum, even if it is difficult to demonstrate empirically. The properties of sound in water and the low levels of light penetration below the surface in many circumstances mean that, for some species, sound is more important than light as the principal source of environmental information. Much evidence points to sound in the low frequencies (< 1 kHz) being most important, except in the cases of some invertebrates (e.g., snapping shrimp) and marine mammals (dolphins, some whales, and seals) that have developed the capacity to both hear and, in some cases, produce complex sounds at much higher frequencies (up to > 200 kHz in smaller cetaceans). Our basic knowledge of the way in which the majority of marine organisms sense sound and then respond behaviorally to different sound stimuli is quite rudimentary for most species and groups. Similarly, the extent to which the introduction of higher background sound levels masks the ability of marine animals to interpret sound signals from the environment is largely unknown, as is their reaction to acute anthropogenic sounds in their vicinity.

For example, we now know that several species of whales have adjusted their communication calls in a manner that suggests they are "raising their voices" or otherwise changing their calls in order to be heard (e.g., Holt et al.,

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2008; Parks et al., 2010). This "Lombard effect" (Lombard, 1911) was originally reported for humans, but it is also seen in terrestrial species such as birds that use sound in social activities (Lengagne, 2008; Slabbekoorn et al., 2010). There is evidence that, in the presence of high levels of background sound, some species simply stop vocalizing, either because they are being disturbed or because, like humans trying to talk in the presence of loud background noise, they give up because communication becomes ineffective. Acoustic masking of marine mammal sounds by increased ambient noise is of particular concern in low-frequency specialists, such as the large baleen whales (Clark et al., 2009). Although it is possible that whales could be especially sensitive (and we know that not all whale species share the same sensitivities), the presence of masking and the Lombard effect leads to two additional questions: (1) are these general effects widespread among marine organisms and, (2) even if they are widespread, are they important to the function and survival of viable populations?

WHY SHOULD WE BE BOTHERED WITH NOISE IMPACTS ON MARINE ORGANISMS?

This question is important for two main reasons. The first is that the industrialization of the ocean is likely to increase in the next few decades. A very large proportion of the manufactured goods and raw materials needed by a growing global economy is being shipped around the world on the ocean. The demand for hydrocarbons is also pushing exploration and production further offshore into deep waters at continental shelf edges. Energy extraction from the ocean, although relatively small at present, is expected to expand rapidly over the next few decades. In coastal areas, recreation is also bringing with it increasing noise levels from pleasure boats. There are real concerns that this process of expanding industrialization and recreation will lead us in small steps toward an intolerable acoustic environment for many marine organisms.

It is vital that "industrialists" engage with solving the problem. If they are not involved, the inexorable march of the *precautionary principle* will slowly but progressively constrain their ability to operate (Gillespie, 2007). Environmental nongovernmental organizations with missions to protect the marine environment will drive the regulatory process. But, while precautionary approaches may be inconvenient to many who have narrow commercial interests, precaution in the face of uncertainty is rational and is an approach that is now deeply embedded in the way that society operates. Reducing uncertainty by increasing

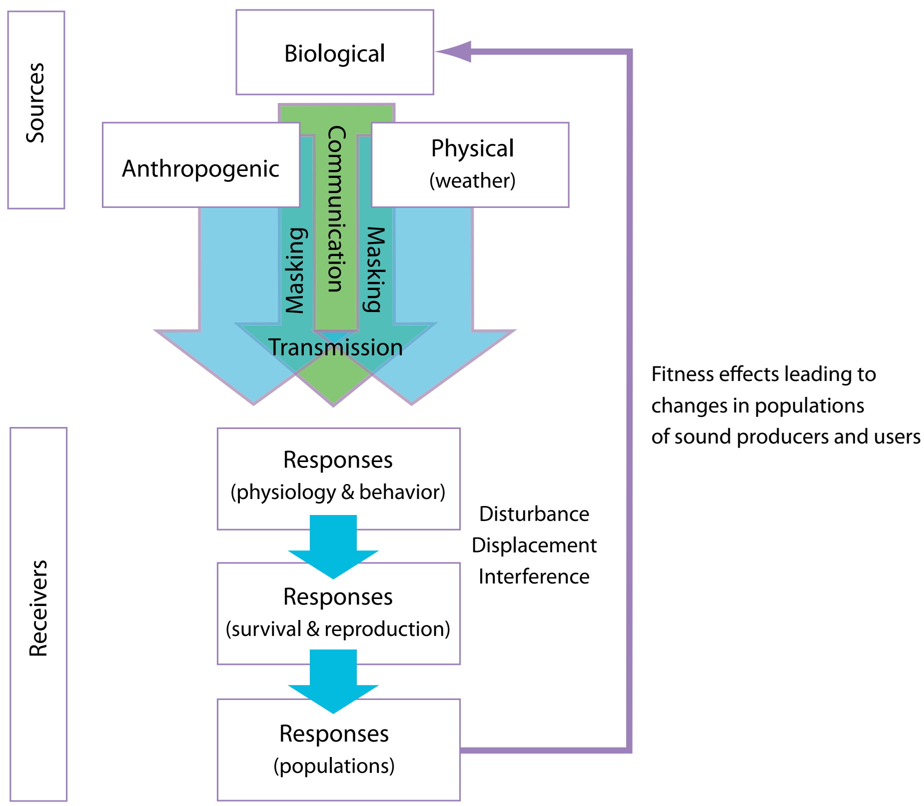

Figure 2. A diagrammatic view of the problem being investigated by the International Quiet Ocean Experiment (IQOE), which defines three major sources of sound in the ocean: physical, biological, and anthropogenic. The sounds involved in marine animal communication and echolocation can be "masked" by physical and other biological sound sources. Communication is likely to have evolved to cope with this type of masking. However, overlaid on this soundscape is new noise added by humans, and marine animals may not be able to handle the additional masking to the same extent. The characteristics of the sound received by organisms ("receivers") will determine responses that could cascade through physiological or behavioral effects that affect an animal's ability to feed, migrate, and breed and that, in turn, may lead to changes in reproduction and survival of the individual. Relatively few physiological and behavioral responses will have a direct effect on populations, but increasing effects of sound could accumulate across individuals, thus pushing these effects gradually to population-level effects.

our knowledge and understanding of the noise problem will be the best guard against excessive precaution and over-regulation.

The second reason for paying attention to the issue of sound in the ocean is even more profound. It is that we are slow to learn from the negative impacts of past industrialization of the ocean. The dangers of causing irreversible declines in the quality of the planet's self-regulating environment are tangible and real. We know that the nonlinear, complex nature of the homeostatic Earth system means that collapses could happen quickly and without much warning. At some point, small changes could lead to very large shifts in the state of the system. Noise may interact with other stressors (e.g., fishing, climate change, pollution) to yield synergistic and/or cumulative impacts. Although there is some evidence that many parts of the ocean show remarkable resilience to the direct exploitation of fish, whales, plankton, and other forms of biological productivity, there is increasing evidence that there are definite limits. *Ecological collapse* is an emotive and poorly defined term. However, if we view it from a human perspective, as ecosystems that can no longer support normal goods and services, local collapse has already occurred as a result of direct exploitation (Bakun and Weeks, 2006; Thurstan and Roberts, 2010). The danger we face is that the uncontrolled introduction of increasing noise, some of which could be avoided with appropriate design, planning, and technological innovation, could add significant further stress to already-stressed oceanic biota. Unless we improve our knowledge of the consequences of noise pollution, we may be cruising blindly toward consequences that, in terms of a simple cost-benefit trade-off, could cost us much more than we will ever gain from ignoring them.

AN EXPERIMENTAL APPROACH

To address the challenging questions posed by the effects of increasing ocean noise, we need to ensure that there is coordination of research, observation, and modeling activities across international boundaries and across disciplines. This need for coordination has stimulated the development of the International Quiet Ocean Experiment (IQOE). This project will employ two methods to help increase understanding of sound in the ocean and its effects. One method will be an *experimental approach* involving the active manipulation of anthropogenic sound sources, either through directed, temporary reductions of anthropogenic sound sources at regional scales, or through planned lulls in noise production (e.g., planned shutdown of offshore construction, diversion of shipping lanes, or temporary presence and absence of sound sources). The second method will be a *comparative approach* through identification of sites that have similar characteristics but differ in terms of their levels of anthropogenic sound.

OCEAN SOUNDSCAPES

A first step in the process of documenting effects of human-produced noise on marine organisms will be to define what we call *ocean soundscapes.* Although we have identified at least 30 sites or networks globally from which current or recent data about ocean noise are available, in almost all cases, the monitoring stations involved have been established to perform specific functions. This lack of coordinated design is reflected in the disparity of sensor designs and of data collection and transmission protocols. We need to find ways to use these data in a unified framework and to establish other measurement systems in order to understand the complex global sound field in the ocean. Building a picture of this global sound field, even in a relatively unrefined form, is a high priority as a baseline for other studies. Sound propagation modeling—based on ship position and activity (from Automatic Identification System data), data for wind and rainfall, and data for seismic surveying, sonars, and pile driving—may provide a general view of the sound fields across the global ocean. The biggest "unknown" in estimating the global soundscape will be the contribution of biological sound, which will require better understanding of animal vocal behavior, particularly when species vocalize in large numbers to produce "choruses." Refinement of this model will be possible with increasing knowledge of sound production from ships and other human activities, many of which are currently poorly characterized.

Ultimately, IQOE would encourage the establishment of a Global Ocean Acoustical Observing System (e.g., Dushaw et al., 2009). Such a system could build on the existing and planned capability of the Global Ocean Observing System and on local and regional systems, such as the US Integrated Ocean Observing System and the Australia Integrated Marine Observing System, by helping to define standards and protocols for sensors and for the analysis, storage, and distribution of data across a global research community.

PREDICTING SOUND FIELDS AND MANAGING NOISE BUDGETS

Establishing the global ocean soundscape, with appropriate statistical consideration of spatial and temporal variance, is a necessary step toward predicting ocean sound fields in particular locations. Sound field predictions can then be challenged with in situ measurements from existing data collection sites, and a process of tuning the sound field models to maximize the fit to the empirical observations will eventually refine ocean soundscape descriptions.

Predicting sound fields in this way should also feed directly into the emerging processes for regulation of offshore human activities and general industrial development. In both the United States and Europe, for example, legislation is moving rapidly to embrace marine spatial planning and to set standards for noise production, principally on a precautionary basis. But, available information is insufficient to build the rationale for spatial management of industrial activities to reduce potential noise impacts on sensitive species or habitats. Characterization of soundscapes on the global scale will enable regional administrations to downscale the soundscapes to reflect their own needs at regional and local scales and to help define the kinds of threshold values that managers often need in order to be able to set legally binding conditions on ocean use. This nested approach to model development and validation is necessary because noise is a problem that needs to be tackled initially at large scales because of the long-range propagation of low-frequency sound. Even local models need to have boundary conditions specified in order to build local noise budgets; it is hoped that IQOE will provide this capability.

EXPLORATION IN DEEP TIME

So, what was the global ocean like before humans arrived? Many have explored this question with respect to the removal of marine mammals and fish, in particular, but we also want to know how noisy the ocean was in the past. In other words, can we back-cast the ocean soundscape to a preindustrial era? Similarly, can we predict the ocean soundscape in the future if current trends continue? Can we create a kind of "Keeling curve" for ocean noise (Keeling et al., 1976)? What is the cost-benefit trade-off if regulations are set to reduce the sound produced by human activities? Questions such as these, though interesting in their own right, have most relevance if they are accompanied by robust functional relationships between sound and the growth or decline of populations of marine organisms.

The challenge and opportunity of IQOE is to coordinate scientific activities on the effects of ocean noise on marine organisms internationally, whether conducted in the academic, governmental, or industry (e.g., Joint Industry Program) sectors. Development of a body of knowledge that begins to illuminate types of responses to different levels of noise in the life functions of individual organisms—such as changes in reproductive rate, growth rate, use of habitat, survival rate, and social structure—is an essential part of the strategy being adopted for this experiment. The species that need to be included vary across the full range of marine organisms, but perhaps could focus principally on some of the keystone or indicator species within major, or important, ecological systems, as well as species already recognized as endangered. Many of the resulting "effects" studies will be small scale and in situ, and some may be possible in controlled conditions in the laboratory. However, all will need to be designed carefully, with controls and also with a view to ensuring that the effects observed can be built into larger-scale strategic models of effects at population and ecological levels, such as the PCAD model referred to previously.

WHERE, WHEN, WHO, AND HOW?

IQOE is being developed under the sponsorship of the Scientific Committee on Oceanic Research (SCOR) and the Partnership for Observation of the Global Oceans (POGO) as a potential joint project, with exploratory funding from the Alfred P. Sloan Foundation and other sources. Through this cooperation, IQOE aims to engage with the global oceanographic community. The intent of IQOE is to combine the talents of physical oceanographers, acousticians, behavioral biologists, ecosystem modelers, and population biologists.

Although IQOE should have a global outreach, we foresee that specific sites or regions will be used, either because they provide extreme examples of locations where sound is likely to have large impacts, or because they are particularly quiet and undisturbed by sound. We propose paying specific attention to areas where relatively rapid changes in industrial activity are occurring or are likely, in order to assess and identify changes in both the soundscapes and responses in marine biota in a comparative way.

IQOE provides a mechanism for focusing and coordinating existing activity. We recognize, for example, that the plans for construction of offshore wind farms in the North Sea represent an opportunity to observe and possibly to carry out experiments on the effects of percussive noise from pile driving. These types of in situ studies could be an important part of the IQOE approach. In some circumstances, planned shutdown of sound sources will add to the knowledge gained from studies that examine animal distribution and abundance before, during, and after disturbance events. There are also some very capable deep ocean laboratories available for conducting experiments on the effects of sound, mainly in the form of naval underwater test ranges that have extensive arrays of acoustic sensors. Some of these facilities have already been used for innovative experimental studies on the effects of sound on beaked whales.

The idea of experimentally shutting down anthropogenic sound sources and observing the effects was a central driver for IQOE development (Ausubel, 2009). Recognizing that marine noise has been increasing, experimental approaches to examining the effects of sound need to involve the reduction, or removal, of anthropogenic sound as well as the introduction of increased sound. However, as the space and time scales get larger, the idea of reducing anthropogenic sound sources gets increasingly difficult. Figure 3 depicts this trade-off between the capacity to carry out experimental manipulations and the size of the temporal and spatial scales involved, and it shows the matrix of different experimental designs and time scales along a gradient of increasing difficulty. In fact, to shut down all human activity in the ocean for only one day—which would be barely long enough for the sound ringing around on the ocean to dissipate—could have a financial cost of more than $10 billion. So, IQOE will focus upon more modest objectives for experimental

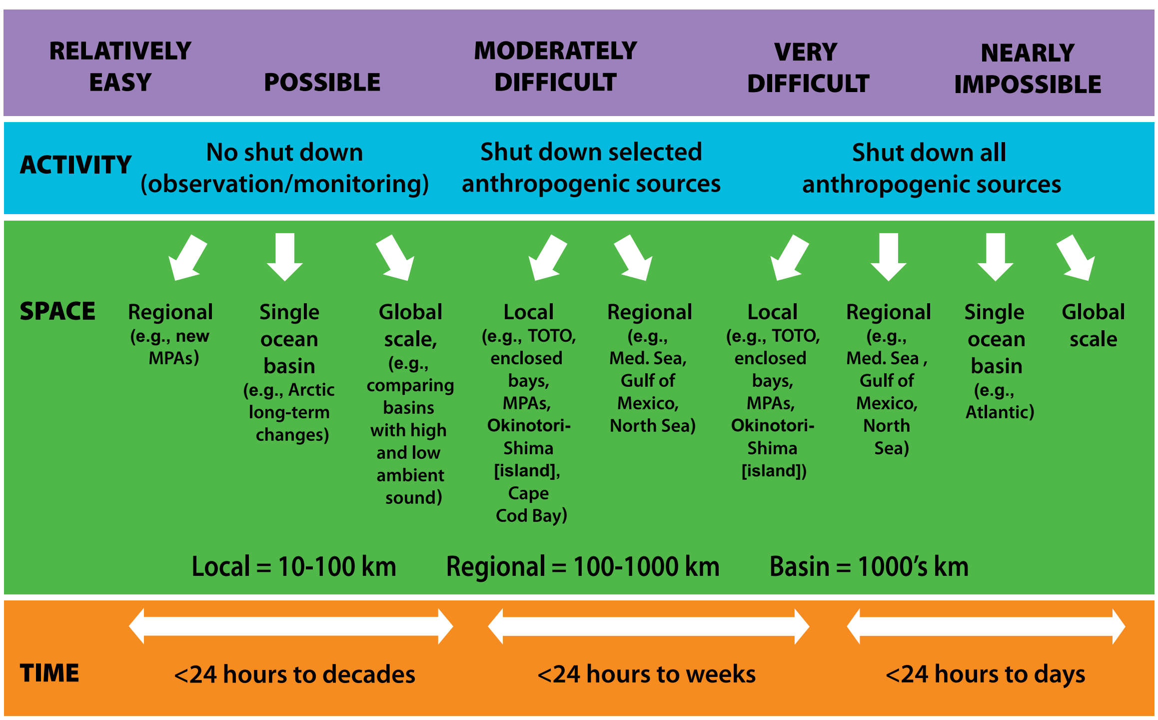

Figure 3. Matrix of quieting feasibility. The difficulty and financial cost of a shutdown of noise sources increases from left to right in the matrix. The feasible time that a noise shutdown could be accomplished decreases from left to right (orange row). Different experimental activities (blue row) might be possible at different spatial scales (green row). The goal of IQOE would be to conduct activities at many different scales. The relationship of the different temporal and spatial scales means that the most feasible approaches are likely to be several experiments carried out over long durations at small scales (i.e., toward the left of the diagram). Two roles that IQOE will play will be (1) to help reduce the difficulty of experiments from left to right in this diagram, and (2) to coordinate experiments of the type defined to the left of the diagram so that they will combine to deliver some of the benefits that would emerge if we were able to carry out experiments lying to the right of the diagram.

manipulation. These objectives will carry even more weight if the results can find general application through the parameterization and/or validation of the global sound field model.

IQOE should also drive technology innovation. Smaller instruments with greater data storage and transmission capacity would allow sound measurement to become more routine and available to a broader range of researchers at affordable prices. In addition, properly promoted, investigation of the five-dimensional world of ocean sound—the three spatial dimensions plus time and the frequency dimension (pitch)—will bring a new depth of understanding to the lives of people who may never have looked at the ocean in this way before.

SCOR and POGO will continue to develop the IQOE idea with an August 30–September 1, 2011, open science meeting (see http://www.IQOE-2011.org) to ensure broad input from the acoustic and oceanographic communities and to enable creation of a science plan for an international research project on sound in the ocean. This plan will build on the work reported in Boyd et al. (2008) and NRC (2003, 2005). The issue of sound in the ocean deserves to be added to the list of global changes that are monitored and studied.

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